

NONLINEAR CROSS TALK CANCELLATION FOR HIGH DENSITY OPTICAL RECORDING

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ABSTRACT

This paper deals with cross talk cancellation for high density optical recording. The data density can be increased reducing the track pitch, as long as cross talk is kept under control. To cope with interference from adjacent tracks, we propose and analyze an adaptive nonlinear cross talk canceller based on a three spot detection system. The optical channel is accurately modeled by a two-dimensional Volterra series. For the sake of simplicity, the performance comparisons presented in this paper are based on the assumption that noise is Additive, White, and Gaussian (AWGN model). Simulation results show the effectiveness of the proposed cross talk canceller.

1. INTRODUCTION

In high density optical disc systems the read-out signal is affected by Inter-Symbol Interference (ISI) along the track that is being read, and by cross talk (XT), i.e., interference from adjacent tracks. A linear channel model based on the Modulation Transfer Function is not able to fully represent these impairments, as also nonlinear terms must be included [1]. In [2], using the optical scalar theory as proposed by Hopkins [3], a nonlinear analytical model based on the Volterra series expansion was identified and tested. The Volterra model is much faster to simulate, and gives much more insight into possible equalization strategies than the optical model.

Using the Volterra model, we analyzed the performance of some classical equalization structures [4], and proposed an innovative nonlinear receiver [5] based on Nonlinear Maximum Likelihood Sequence Estimation (NMLSE).

In previous works, we considered only ISI. In this paper we turn to the problem of cross talk cancellation. In particular, we present a Cross Talk Canceller (XTC) based on a three spot detection system. In this architecture, the information stored in the two adjacent tracks is estimated using classical (nonlinear) equalization algorithms. Then, an adaptive XT canceller cleans up the

signal of the central track. Finally, the signal is processed with one of the nonlinear algorithms developed so far to combat nonlinear ISI, and final decisions are taken.

The proposed XTC shows significant performance improvement with respect to a classical receiver without XT cancellation. The performance comparisons presented in this paper are based on a two-dimensional Volterra model for the optical channel. For the sake of simplicity, in this paper we compare different receivers in presence of Additive White Gaussian noise (AWGN).

The paper is organized as follows. In Section 2 the nonlinear channel model, that takes into account both ISI and XT, is presented. In Section 3 two equalization algorithms suited for nonlinear channels, namely Nonlinear Adaptive Volterra Equalization (NAVE) and Nonlinear Maximum Likelihood Sequence Estimation (NMLSE), are introduced and briefly described. Section 4 is devoted to the description of the cross talk canceller. Simulation results and concluding remarks are given in the final sections.

2. THE NONLINEAR CHANNEL MODEL

The optical scalar theory developed by Hopkins [3] is based on the concatenation of the following facts. Light, generated by the laser source, propagates through the lens towards the disc surface. Field propagation is mathematically described by the two-dimensional Fourier transform of the scalar input field. Disc reflectivity can be modeled making use of the Fourier series for periodic structures. The incident field is reflected in proportion to the disc phase profile, and is back-propagated to the detector (usually through the same lens used in the forward path). Back-propagation can be modeled by another two-dimensional Fourier transform. Finally, the photodiode converts the incident field into an electrical signal. This optical model can be used to evaluate the read-out signal also if some amount of light impinges neighboring tracks, i.e., in presence of cross talk.

The analysis carried out through the physical model shows that a linear model for the optical system is not an

accurate approximation for high density optical discs, and that second-order terms must be included as well [2].

2.1. The Volterra Model

In general, the functional input output relationship $y(t) = f[x(t)]$ of a nonlinear system can be represented as [7]:

$$y(t) = h_0 + \int h_1(\tau)x(t-\tau)d\tau + \iint h_2(\tau_1, \tau_2)x(t-\tau_1)x(t-\tau_2)d\tau_1 d\tau_2 + \dots \quad (1)$$

where h_0 is the response to a zero input, $h_1(t)$ is the impulse response of the linear part of the system, and higher order kernels can be viewed as higher order impulse responses.

According to the scalar theory, the propagation of light is represented by a chain of linear transformations followed by the quadratic distortion generated by the photodetection process. As long as the scalar theory holds, we have verified that a second order Volterra model leads to an accurate analytical description of the read-out process [2].

In presence of cross talk, we have a nonlinear system with many inputs and one output. Let $x_0(t)$ and $x_i(t)$ be the data stored on the central track, and on adjacent ones. Then, the output signal is

$$y(t) = h_0 + \sum_i \int h_1^i(\tau)x_i(t-\tau)d\tau + \sum_i \iint h_2^i(\tau_1, \tau_2)x_i(t-\tau_1)x_i(t-\tau_2)d\tau_1 d\tau_2 + \sum_i \sum_{j \neq i} \iint h_2^{ij}(\tau_1, \tau_2)x_i(t-\tau_1)x_j(t-\tau_2)d\tau_1 d\tau_2 \quad (2)$$

where $h_1^i(\tau)$ and $h_2^i(\tau_1, \tau_2)$ ($i \neq 0$) represent linear and nonlinear XT due the i -th track alone, while $h_2^{ij}(\tau_1, \tau_2)$ ($j \neq i$) takes care of nonlinear combinations of data stored in different tracks. We have verified that in practice we need consider only XT terms due to the two adjacent tracks ($i, j = \pm 1$).

An appropriate kernel identification procedure of all Volterra kernels was developed in previous works [2].

Simulations have shown that, even at the Compact Disk Digital Audio (CDDA) density, the contributions of second order terms are not negligible, and that nonlinear contributions become worse as the information density is increased [2].

Fig. 1 shows the Volterra output $y(t)$, along with the output without XT, and XT terms alone (arbitrarily shifted, to show them better). The data density along tracks is CDDA, and the track distance $d = 0.7 \mu m$ (instead of $d = 1.6 \mu m$). We see that an exact representation of the read-out signal requires cross talk kernels.

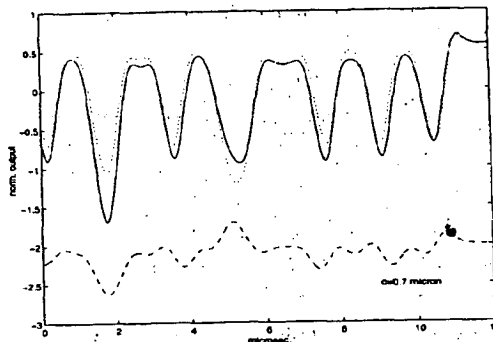


Figure 1: Output signal (solid line); Volterra's output without XT (dotted); and XT terms (dashed).

3. EQUALIZATION TECHNIQUES FOR NONLINEAR CHANNELS

The optimum linear receiving filter for a nonlinear channel [7] consists of a bank of matched filters, followed by linear transversal filters of infinite length. The number of matched filters grows exponentially with the channel memory, hence this optimal solution is hardly feasible. Therefore we look for other equalization schemes, offering a good trade-off between complexity and performance. In this work adjacent tracks are equalized by the Nonlinear Adaptive Volterra Equalizer (NAVE) [6]. For the main track, we consider both NAVE and the nonlinear receiver (NMLSE) proposed in [5]. These architectures are briefly described in the following paragraphs.

3.1. Nonlinear Adaptive Volterra Equalizer (NAVE)

The channel input-output relationship suggests the use of a nonlinear equalizer, namely a second order discrete-time Volterra system. The equalizer output is

$$z_n = \sum_{n_1} c_{n_1} r_{n-n_1} + \sum_{n_1} \sum_{n_2} c_{n_1, n_2} r_{n-n_1} r_{n-n_2} \quad (3)$$

where r_n represents the noisy channel output samples. A second order Volterra equalizer is able to cancel first and second order interference, but produces third and fourth order terms [8]. In the specific cases considered in this paper, these higher order terms were negligible.

The weights in the above equation are adaptively updated, for instance according to the Least Mean Square (LMS) algorithm. This equalizer structure is known as Nonlinear Adaptive Volterra Equalizer (NAVE) [6], and is a nonlinear extension of MSE equalization.

3.2. Nonlinear Maximum Likelihood Sequence Estimation (NMLSE)

To realize an adaptive Maximum Likelihood Sequence Estimator (MLSE) in the case of linear channels, we can use an adaptive Matched Filter (MF) followed by a Viterbi Detector (VD) [9]. To extend the MLSE structure to the nonlinear optical channel, we add a Non-Linear Canceller (NLC), for nonlinear ISI suppression. Once nonlinear distortion is canceled, the VD can compute metrics the usual way. The combination of the NLC, the adaptive MF and the VD leads to the NMLSE [5].

Fig. 2 shows a simplified block diagram of the proposed NMLSE (in particular, updating of the adaptive matched filter coefficients and of the autocorrelation estimator are not shown).

For nonlinear ISI suppression, the samples r_i of the received signal $r(t) = y(t) + n(t)$ are processed by a nonlinear combiner, that produces products of couples of samples $r_h r_k$, $1 \leq h \leq N$, $1 \leq k \leq N$. If N is the number of samples r_i , N^2 products u_i are generated, and fed to the Non-Linear Canceller (NLC). The weights w_i of the NLC are updated by the stochastic gradient algorithm. The NLC and the MF form a preliminary equalizer. Then, the samples h_n are affected almost only by linear distortion, and are processed by the MLSE Viterbi detector.

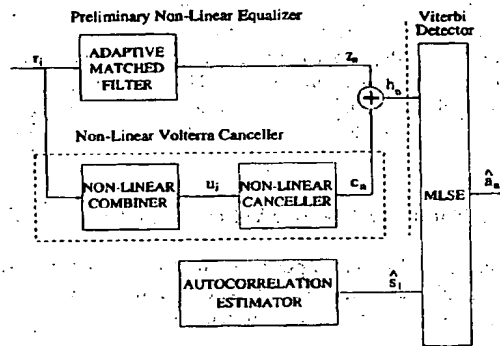


Figure 2: Simplified block diagram of NMLSE.

4. CROSS TALK CANCELLER

To take care also of cross talk, we adopt a multispot receiver, along with a cancellation algorithm.

We assume that all spots are characterized by identical optical parameters. Our receiver uses three spots, that read the main track and the two adjacent ones. Let the corresponding read-out signals be $y(t)$, $y_1(t)$, and $y_2(t)$, respectively. Note that $y_1(t)$ and $y_2(t)$ suffer from

XT from two other neighboring tracks. We do not try to cancel these terms. The three read-out signals are also corrupted by additive gaussian noise.

A simplified block diagram of the XT canceller is shown in Fig. 3. Note that all delays are understood. For instance, the estimates $\{\hat{a}_{1n}\}$ and $\{\hat{a}_{2n}\}$ of symbols stored in the adjacent tracks are produced with a delay equal to $(N-1)/2$, where N is the length of the adaptive NAVES, fed by the samples r_{1n} and r_{2n} . Another delay is produced by the NAVE (or NMLSE) that takes the final decisions \hat{a}_{un} . Hence, also the error signal used to update the coefficients of all the adaptive filters is delayed, and must be multiplied by delayed replicas of estimated data.

Linear combinations of the (nonlinearly) estimated data $\{\hat{a}_{1n}\}$ and $\{\hat{a}_{2n}\}$, obtained through two adaptive filters with N coefficients that try to reproduce the interference from neighboring tracks, are subtracted from the samples r_n of the main track. We have not considered more complex XT cancellers, taking into account also products of $\{\hat{a}_{1n}\}$, $\{\hat{a}_{2n}\}$ and of the (estimated) data along the central track, so far. This work is in progress.

A third adaptive filter with M taps subtracts an estimate of ISI of the central track. We found that ISI cancellation eases the identification of the coefficients of the XT canceller.

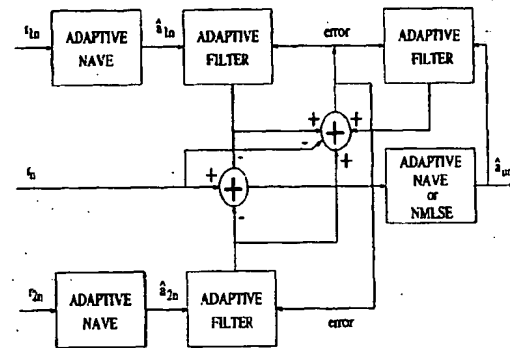


Figure 3: Block diagram of the XT canceller.

The coefficients g_{1i} , g_{2i} , $i = 0, \dots, N-1$ and h_i , $i = 0, \dots, M-1$ of the three filters are adaptively calculated, to minimize the mean-square error

$$\mathcal{E} = E \left[\left| r_n - \sum_{i=0}^{N-1} g_{1i} \hat{a}_{1i} - \sum_{i=0}^{N-1} g_{2i} \hat{a}_{2i} - \sum_{i=0}^{M-1} h_i \hat{a}_{ui} \right|^2 \right] \quad (4)$$

Then, if we let

$$\hat{\mathbf{a}} = \{\hat{a}_{10}, \dots, \hat{a}_{1N-1}, \hat{a}_{20}, \dots, \hat{a}_{2N-1}, \hat{a}_{u0}, \dots, \hat{a}_{uM-1}\} \quad (5)$$

and

$$\mathbf{z} = \{g_{10}, \dots, g_{1N-1}, g_{20}, \dots, g_{2N-1}, h_0, \dots, h_{M-1}\} \quad (6)$$

the filter taps are updated by the stochastic gradient algorithm, namely

$$\begin{aligned} \mathbf{z}^{k+1} = & \mathbf{z}^k - \delta_1 \sum_{i=0}^{N-1} g_{1i} \hat{a}_{1i} + \\ & - \delta_2 \sum_{i=0}^{N-1} g_{2i} \hat{a}_{2i} - \delta_u \sum_{i=0}^{M-1} h_i \hat{a}_{ui} + r_n \hat{\mathbf{a}} \end{aligned} \quad (7)$$

Note that in the above equation delays are understood, as in Fig. 3. Finally, the estimated XT contributions of adjacent tracks are subtracted, and the symbols of the central track are obtained (by NAVE or NMLSE) from

$$\bar{r}_n = r_n - \sum_{i=0}^{N-1} g_{1i} \hat{a}_{1i} - \sum_{i=0}^{N-1} g_{2i} \hat{a}_{2i} \quad (8)$$

5. SIMULATION RESULTS

Simulations have been carried out assuming the optical parameters of the Compact Disc Digital Audio (CDDA) system as a reference: the numerical aperture of the objective $NA = 0.45$, the laser wavelength $\lambda = 0.780 \mu\text{m}$, and the tangential velocity $v = 1.25 \text{ m/s}$.

Since the read-out system is nonlinear, the definition of the energy per information bit may be ambiguous. We adopt the following notation. Let us denote the peak to peak steady state response (to a long sequence of pits and lands, respectively) as V_{pp} . Then, if T is the bit duration, the bit energy is expressed by the quantity $E = T(V_{pp}/2)^2$. We evaluate the bit error rate (BER) as a function of the signal-to-noise ratio E/N_0 , where N_0 is the one-sided power spectral density of additive Gaussian noise.

Simulations have been carried out with different information densities (for instance, in the following $1.25 \times \text{CDDA}$ means that the spatial density along the tracks is 1.25 times the CDDA density). The distance d between adjacent tracks ranges from $1.6 \mu\text{m}$ (standard CDDA) to $0.7 \mu\text{m}$.

To get an idea of the effects of linear cross talk, and of nonlinear cross talk (that we do not try to cancel), we evaluated the performance of the cross talk canceller considering both the complete second order nonlinear Volterra model, and a simplified model without second order cross talk contributions. The simulation results are presented in the following paragraphs.

5.1. Cross Talk Canceller with NAVE (NAXTC)

In this receiver the estimated symbols $\{\hat{a}_{1i}\}$ and $\{\hat{a}_{2i}\}$ are obtained by two NAVE equalizers. Another NAVE equalizer is used to decide the useful symbols of the central track, after cross talk cancellation.

We considered NAVE algorithms with $N = 5$ linear taps and $N^2 = 25$ nonlinear ones. Weights are updated according to the LMS algorithm, with step size equal to 10^{-3} for linear taps, and 10^{-6} for nonlinear ones. Each cross talk canceller has $N = 5$ taps, updated according to the steepest descent algorithm with step size 10^{-3} .

Fig. 4 shows the performance of the complete cross talk canceller (NAXTC) at the CDDA density, with distance between adjacent tracks $d = 0.7 \mu\text{m}$. For comparison, also the performance of NAVE without XT cancellation is shown. We can see that the performance is unacceptable. We also see that the NAXTC almost completely eliminates the linear part of XT, but there is still room for some improvement by a second order XT canceller.

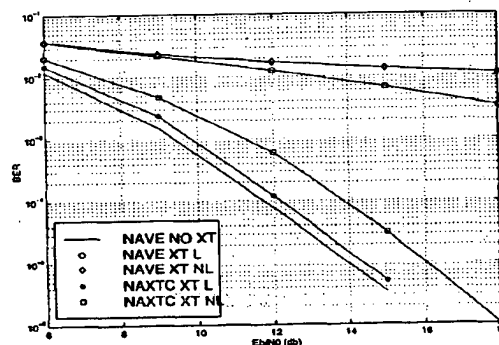


Figure 4: Performance of NAVE and NAXTC (CDDA density). NAVE NO XT: NAVE (without XT); NAVE XT L: NAVE (linear XT only); NAVE XT NL: NAVE (linear and nonlinear XT); NAXTC XT L: NAXTC (linear XT only); NAXTC XT NL: NAXTC (linear and nonlinear XT).

Figs 5 and 6 show the performance of NAXTC when the density is $1.25 \times \text{CDDA}$ and $1.43 \times \text{CDDA}$, respectively.

If we increase the density further, the NAXTC receiver fails, due to strong linear and nonlinear ISI. In this case, we need a more complex algorithm for the main track, like, e.g., the NMLSE.

5.2. Cross talk canceller with NMLSE (NMXTC)

Two NAVE equalizers estimate the symbols $\{\hat{a}_{1i}\}$ and $\{\hat{a}_{2i}\}$, as in NAXTC. However, after cross talk cancellation we use an NMLSE receiver for the main track.

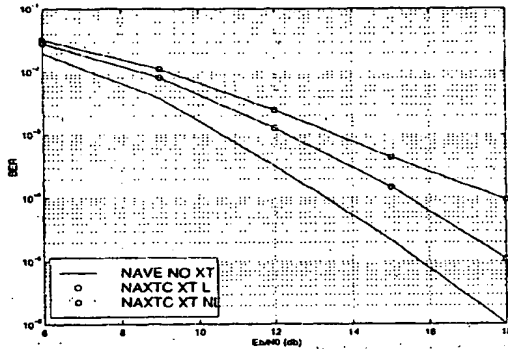


Figure 5: Performance of NAXTC (1.25xCDDA).

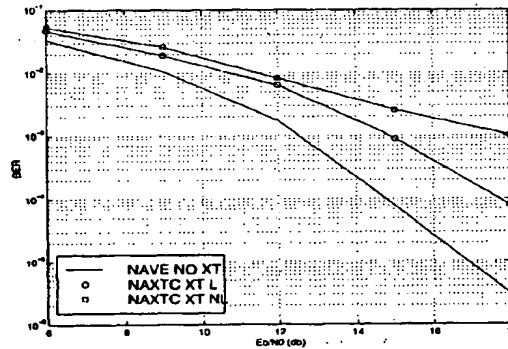


Figure 6: Performance of NAXTC (1.43xCDDA).

The NMLSE considered here has an adaptive matched filter with $N = 5$ linear taps and an NLC with $N^2 = 25$ nonlinear ones. Weights are updated according to the LMS algorithm, with step size equal to 10^{-3} for linear taps, and 10^{-5} for nonlinear ones. The decision delay, i.e., the trellis length that is kept in memory, is $L = 30$, and $S = 128$ trellis states are considered. The cross talk canceller is the same as in the previous case.

Figs 7, 8, 9, and 10 show the performance of NMXTC at linear densities ranging from CDDA to $1.67 \times \text{CDDA}$, with distance between adjacent tracks $d = 0.7 \mu\text{m}$. We can see that NMXTC gives acceptable performance also at $1.67 \times \text{CDDA}$. Further improvements require more trellis states, hence increased complexity.

Part of the performance degradation at high densities is due to wrong decisions on adjacent tracks, hence to incomplete XT cancellation. Fig. 11 compares the performance of NMXTC with perfect knowledge of data stored on adjacent tracks (which is not available, of course), and with the estimated (i.e., noisy) data.

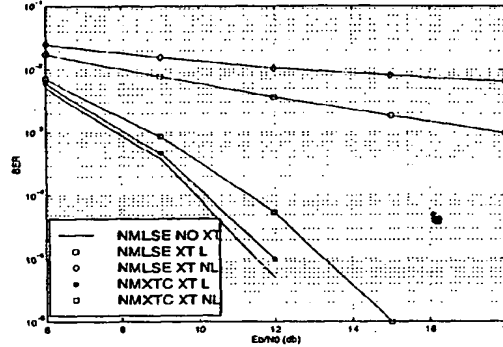


Figure 7: Performance of NMLSE and NMXTC (CDDA density). NMLSE NO XT: NMLSE (without XT); NMLSE XT L: NMLSE (linear XT only); NMLSE XT NL: NMLSE (linear and nonlinear XT); NMXTC XT L: NMXTC (linear XT only); NMXTC XT NL: NMXTC (linear and nonlinear XT).

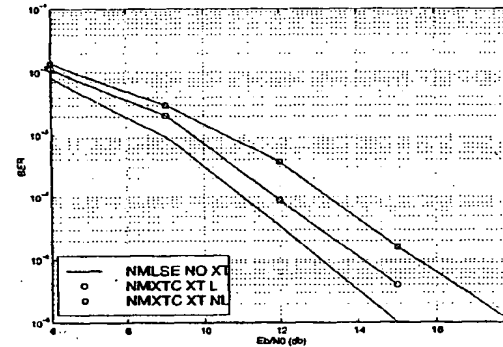


Figure 8: Performance of NMXTC (1.25xCDDA).

6. CONCLUSIONS

In this paper cross talk cancellation algorithms based on a three spot detection system have been proposed and evaluated. The nonlinear channel is represented by a suitable model based on the Volterra series. Simulation results show the effectiveness of the proposed receiver architectures, which are based on nonlinear detection of data on adjacent tracks, and linear cross talk cancellation, followed by nonlinear equalization (NAVE) or Nonlinear Maximum Likelihood Sequence Estimation (NMLSE). The latter receiver offers the best performance, at the cost of increased complexity. We have shown that, with a multispot detection system, the information density can be significantly increased in the tangential direction (by a factor of 1.67) and in the radial direction (by a factor $1.6/0.7=2.3$), with reasonable

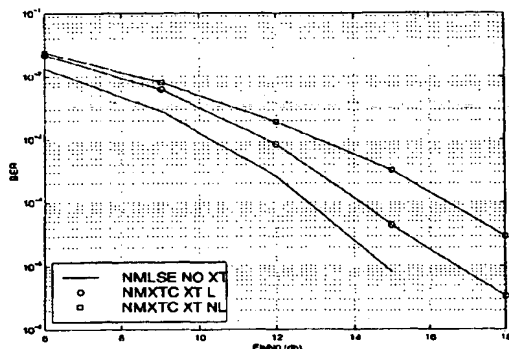


Figure 9: Performance of NMXTC (1.43xCDDA).

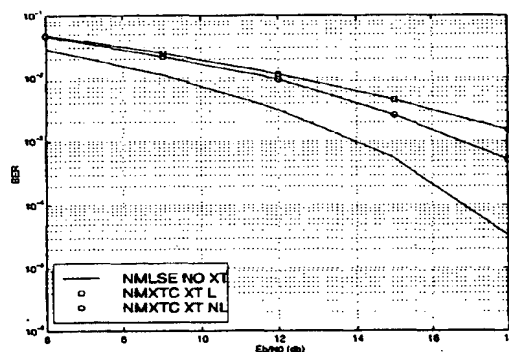


Figure 10: Performance of NMXTC (1.67xCDDA).

computational complexity. The evaluation of the performance of nonlinear detection of adjacent data, followed by nonlinear (i.e., first and second order) cross talk cancellation is in progress.

7. REFERENCES

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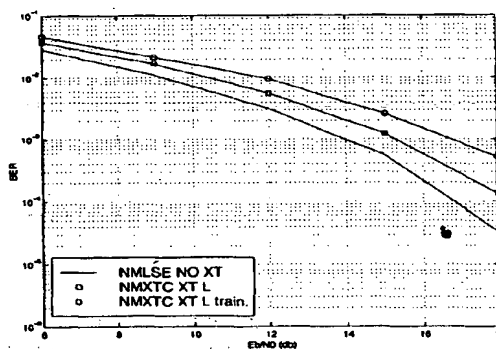


Figure 11: Performance degradation of NMXTC due to wrong decision on adjacent tracks (1.67xCDDA). NMLSE NO XT: NMLSE (without XT); NMXTC XT L: NMXTC (linear XT only); NMXTC XT L train.: NMXTC (linear XT and exact decisions on adjacent tracks).

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